II. "On Time-lag in the Magnetisation of Iron." By J. A. Ewing, B.Sc., F.R.S., Professor of Engineering in University College, Dundee. Received June 18, 1889.

When any change is made to take place in the magnetic force acting on a piece of soft (annealed) iron, a considerable time elapses before the resulting change in the magnetism of the piece is complete. The sluggishness which soft iron exhibits in assuming its full magnetism when a magnetic force is imposed upon it was referred to as follows in the account which I wrote, some years ago, of experiments on the magnetic qualities of iron:—*

"Some evidence was given that, in addition to much static hysteresis, there is a small amount of viscous lagging in the changes of magnetism which follow changes of magnetising force. I repeatedly observed that when the magnetising current was applied to long wires of soft iron, either gradually or with more or less suddenness, there was a distinct creeping up of the magnetometer deflection after the current had attained a steady value, as measured by the deflection of the galvanometer through which it passed. This action was sometimes so considerable as to oblige me to wait for some minutes before taking the magnetometer reading."

In his paper "On the Behaviour of Iron and Steel under the Operation of Feeble Magnetic Forces,"† Lord Rayleigh has remarked on the same phenomenon in soft iron. In his experiments the relation of the magnetic force to the resulting magnetisation of the specimen was studied by means of a magnetometer furnished with a "compensating coil," through which the magnetising current passed, and which was so placed that its action on the needle of the magnetometer balanced the action of the iron, giving no deflection. When very feeble magnetic forces were applied to hard iron or to steel, he found that a perfect balance might be obtained by adjusting the position of the compensating coil, and so established the fact that the susceptibility to small magnetic forces, or to small changes of force, is a definite quantity, which is independent of the amount of the small change of force. He observes that with hard iron and steel the compensating coil might be set so that neither at the moment of closing the circuit of the magnetising current nor afterwards was there any deflection of the magnetometer, which means that (so far as the magnetometer can decide) the metal assumes its magnetic state instantaneously. He goes on to say that soft iron shows much more complicated effects: "When the coil was so placed as to reduce as much as possible the instantaneous effect, there ensued a drift of the

* "Exp. Researches in Magnetism," 'Phil. Trans.,' 1885, p. 569, § 52.
† 'Phil. Mag.,' March, 1887, p. 230.

magnetometer needle . . . . in such a direction as to indicate a continued increase of magnetisation. Precisely opposite effects followed the withdrawal of the magnetising force. The settling down of the iron into a new magnetic state is thus shown to be far from instantaneous. On account of the complication caused by the free swings of the needle, good observations on the drift could not be obtained with this apparatus, but it was evident that whilst most of the anomalous action was over in 3 or 4 seconds, the final magnetic state was not attained until after about 15 or 20 seconds." Lord Rayleigh then cites my observation, quoted above.

In the following experiments Lord Rayleigh's method of the compensating coil has been made use of for the purpose of examining in some detail this "drift," or "creeping," or quasi-viscous change of magnetism which follows any change in the magnetic force acting on soft iron.

The magnetometer was a light Thomson mirror directed by the horizontal component of the earth's field, and having a free period of double swing amounting to nearly $1\frac{1}{2}$ seconds. The specimen of iron used in the greater number of the experiments was a straight piece of thick wire 0·404 cm. in diameter and 39·6 cm. long, over which was slipped a tube with a magnetising solenoid wound upon it. The wire was set in a vertical position, magnetically west of the magnetometer, with its top end on a level with the mirror, and generally 6 cm. distant from it. The compensating coil was wound on a wooden frame, which could be moved along a "geometric slide" towards or from the magnetometer in the east-west line through the mirror, for the purpose of balancing the magnetic effect of the iron. In some of the experiments another compensating coil was used to balance the effect on the magnetometer of the magnetising solenoid, but generally the simpler plan was followed of including the effect of the solenoid in the determination of the compensating coil's action on the magnetometer.

To prevent the vertical component of the earth's field from acting on the iron, a second magnetising solenoid was wound over the first, and a constant current of the proper strength to neutralise the earth's field was maintained in it without interruption. The main magnetising current was regulated by having in its circuit a box of resistance coils, and also the liquid slide described in my former paper.* This allowed the magnetic force to be changed either suddenly or gradually, and the slide also allowed the method of demagnetising by numerous reversals of a continuously diminishing magnetic force to be resorted to whenever it was desired to reduce the iron to a magnetically neutral state.

To soften the wire it was heated to redness by being slowly drawn

* *Loc. cit.*, § 18, p. 537.

through a Bunsen flame. After it was put in place the method of reversals was applied to extract a small amount of magnetism which it had acquired in being handled. In the experiments which I shall first describe the effects of very feeble magnetic force were examined by making and breaking the circuit of the magnetising solenoid while the current was adjusted to produce a force of less than 0·1 c.g.s. It was found that the *immediate* effect of each make and break could be balanced very exactly by adjusting the position of the compensating coil, and so long as the magnetising force was considerably less than 0·1 c.g.s. the distance at which the coil had to be set to give this balance was as nearly as possible independent of the value of the force, and was the same for "break" as for "make." The position of the coil was adjusted so that at the instant when the magnetising current was set up by pressing down a contact key, there was no sudden deflection of the magnetometer mirror to either side. When the compensation was right the spot of light simply began to drift slowly towards the side corresponding to increase of magnetism; when there was over-compensation, the spot of light gave a quiver to the opposite side before beginning to drift, and the position of the coil was adjusted by drawing it back little by little until the quiver on pressing down the key disappeared. The amount of magnetism that was balanced was afterwards measured by removing the iron, but leaving the magnetising solenoid and the compensating coil in place, and observing the deflection of the magnetometer when the same current was passed through the empty solenoid and the compensating coil. This determined the immediate magnetic effect of the magnetising current on the iron, and the subsequent creeping up of the magnetism was of course determined by observing the drifting of the magnetometer needle which had ensued after applying the current while the iron was in its place.

In the following experiment a current of 21 on the arbitrary galvanometer scale (equivalent in this case to a magnetising force of 0·044 c.g.s.) was made, after the wire had been completely demagnetised, and after the compensating coil had been adjusted to balance the immediate effect. Magnetometer readings were taken 5 seconds and 60 seconds after "make;" and at 60 seconds the current was broken, and magnetometer readings were taken 5 seconds and 60 seconds after "break." The immediate effect (balanced by the compensating coil) was equivalent to twenty-five divisions of the magnetometer scale.

Time after "make."	Magnetometer.	Time after "break."	Magnetometer.
0	0	0	13
5″	8	5″	5
60″	13	60″	0

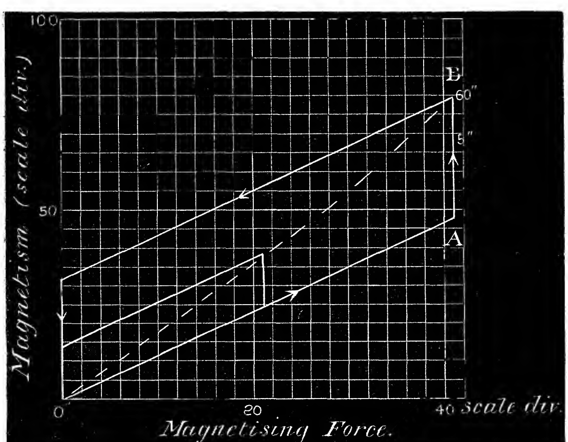
Adding to these the equivalent of the compensating coil, we see that just after the immediate magnetising force was suddenly applied, the value of the magnetism was 25, which increased after 5 seconds to 33, and after 1 minute to 38; and that when the magnetising force was suddenly withdrawn, there was at first a residual magnetism of 13, which fell to 5 in 5 seconds, and disappeared altogether in less than 1 minute.

Next a current 41 (producing a magnetising force of 0·084 c.g.s.) was made and broken in the same way. The compensating coil scarcely required to be moved from its former position, and its equivalent on the magnetometer was now 48. The column headed "total" gives the sum of the magnetometer reading and the part balanced by the compensating coil.

Time after "make."	Magnetometer. Observed.	Magnetometer. Total.	Time after "break."	Magnetometer.
0	0	48	0	31
5″	20	68	5″	13
60″	31	79	60″	4

Here out of the whole original residue of 31, a small part refused to disappear after the lapse of a minute, and it is probable that with this magnetising force some of the residual magnetism is permanent.

Fig. 1.



The above results are shown in fig. 1 where the arrows indicate the sequence of magnetic changes. One scale division of the magnetometer is here equivalent to 0·0177 c.g.s. units of $\mathfrak{I}$ (intensity of

magnetism). The magnetic force due to the solenoid may be taken as approximately equal to the whole magnetic force (although the rod was barely 100 diameters long, this length should be sufficient to approximate to endlessness when one is dealing with very low values of magnetic susceptibility). On this assumption, one scale division of the galvanometer is equivalent to 0·0021 of $\mathfrak{H}$; the initial instantaneous susceptibility, that is, the gradient $d\mathfrak{I}/d\mathfrak{H}$, is 9·9, and the initial instantaneous permeability ($d\mathfrak{B}/d\mathfrak{H}$) is 125. This value has been confirmed by a number of independent observations made with the same piece of annealed wire, and with another piece cut from the same hank and also annealed. Taking the magnetism acquired after 1 minute, the initial susceptibility as regards that is about 15.

Precisely similar results have been obtained by reversing feeble magnetic forces. So long as the forces are very small, the compensation for "reverse" is the same as for "make" and for "break," and the creeping of the magnetism in any given time after make, break, or reverse is nearly proportional to the amount of the preceding change of magnetising force.

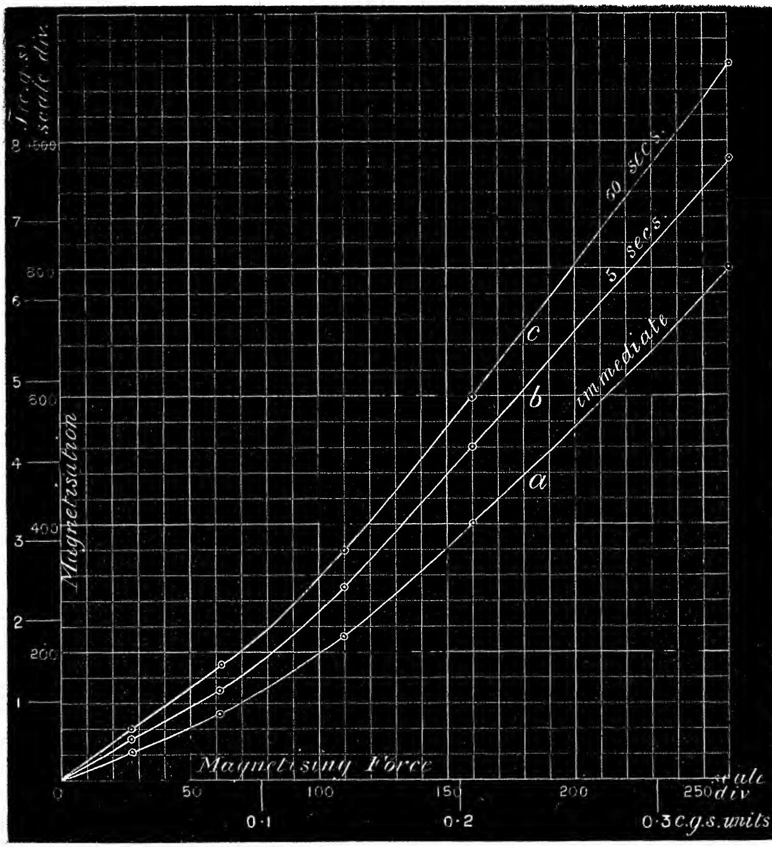
In the following experiments the magnetising force was raised to higher values, at which this proportionality no longer held good. As before, the compensating coil was adjusted for each current to balance the effect of "make," the iron being demagnetised by reversals immediately before the "make." When a stronger current was applied, the coil had to be pushed nearer the magnetometer: but up to forces of 0·3 c.g.s. or so, it was practicable to secure an instantaneous balance by doing so. Observations of the drift were taken at 5 and 10 second intervals during 1 minute.* These are given

Table I.

Time after "make."	Current.				
	27	62	110	161	261
seconds.	Magnetometer + comp. coil.				
0	47	107	224	395	798
5	65	145	304	525	974
10	72	159	327	560	1071
15	74	165	339	573	1089
20	77	169	344	581	1098
25	79	171	347	586	1104
30	79	173	350	590	1109
40	80	175	354	595	1116
50	80	177	355	598	1120
60	80	177	357	600	1124

* To make the drift large the top of the wire was this time only 4 cm. from the magnetometer.

Fig. 2.



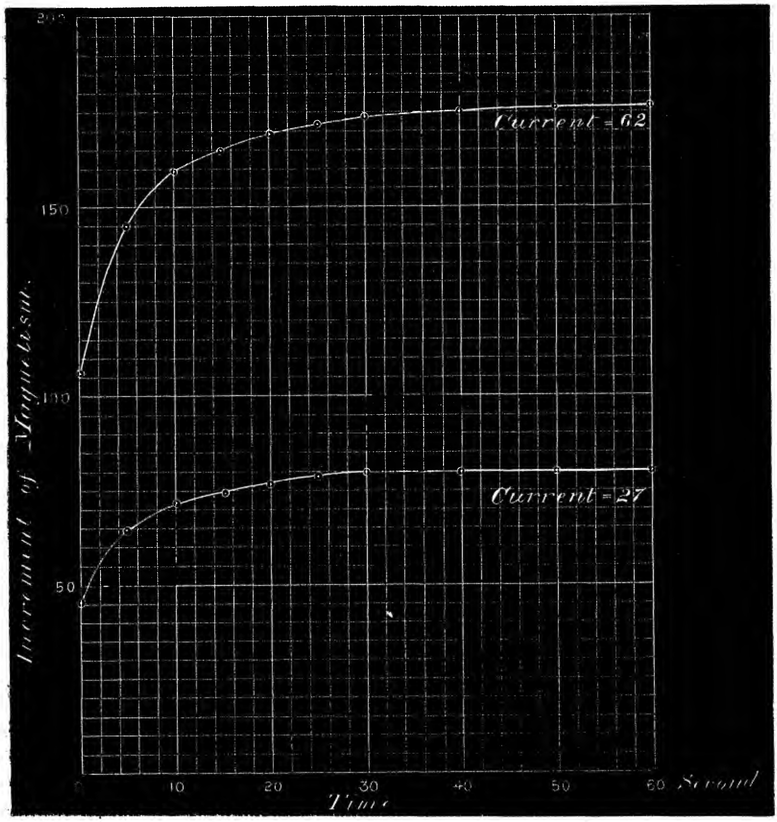
on p. 273, the equivalent effect of the compensating coil being added in each case to the actual magnetometer readings.

In fig. 2, curves are drawn to show the relation of the current to (a) the immediate magnetisation; (b) the magnetism after 5 seconds; and (c) the magnetism after 1 minute. The gradient of the curve (a) at and near the origin is the same as that of the corresponding curve in fig. 1, when allowance is made for difference of scales. In the present instance one division of current is 0·0013 of $\mathfrak{H}$, and one division of magnetism is 0·008 of $\mathfrak{I}$. The gradient begins to increase very sensibly when $\mathfrak{H}$ exceeds about 0·07.

Some of the results of Table I are also shown in fig. 3, which gives time curves of the growth of magnetism for the first two stages (currents 27 and 62). Similar curves for the other stages may readily be constructed from the table. It should be noticed that the time

rate of creeping is by no means excessively great in the first instants after contact is made; it is on this fact indeed that the practicability of the method depends.

FIG. 3.



Similar differences between the immediate and ultimate increments of magnetism present themselves when the magnetising force is increased step by step. In the following experiment the compensating coil was set so as to balance the immediate effect of a feeble magnetising current. Then such a current was applied, and the creeping up of the magnetism during 1 minute was observed. At the end of the minute the current was increased by a small step, and it was found that the compensation was still correct or very nearly so: in other words that the immediate effect of this small increase of magnetising force bore the same or very nearly the same proportion

to the increment of force as at the beginning of the process of magnetisation. The creep up of magnetism was again observed during a minute: then another small step up of the current was made, and so on. The compensation remained nearly correct for a number of steps, but as the process was continued up the curve of magnetisation, it became apparent that the immediate effect was *increasing*, in other words that there was under-compensation, and that the compensating coil would have to be moved a little forward if an exact balance was to be maintained. The results of this experiment are given below (Table II), and are exhibited in fig. 4. The magnetising current was increased from one to another of the successive values shown in the table at intervals of 1 minute in each case, by moderately quick movements of the sliding block in the liquid rheostat. The changes of magnetic force were therefore not quite sudden; each of them took perhaps a quarter of a second to complete.

Table II.

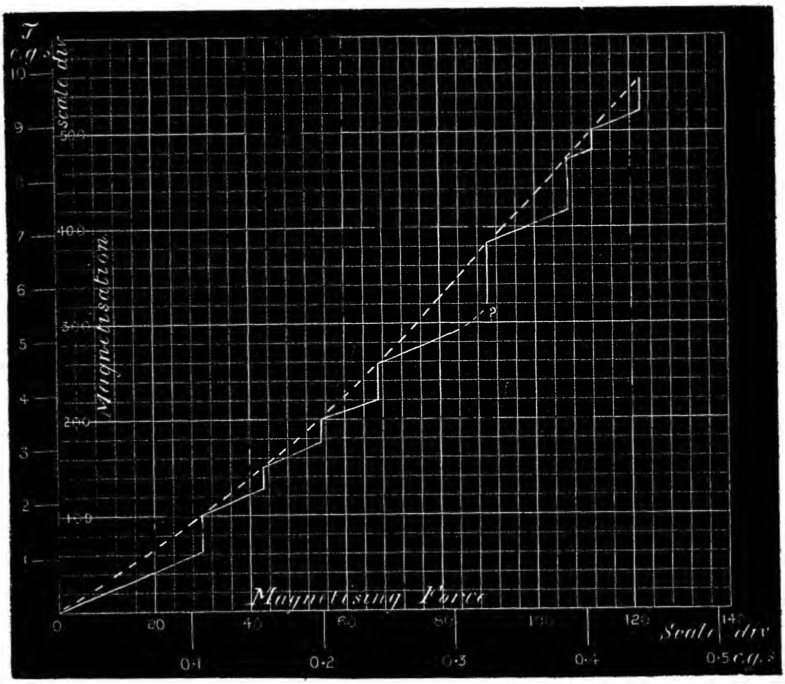
Magnetising current.		Immediate magnetic effect of step.	Additional increase of magnetism in 1 minute.	Total magnetism (after 1 minute).
Step.	Total.			
30	30	63	36	99
13	43	27	23	149
12	55	26	22	197
12	67	25	35	257
23	90	(49+)	(75−)	381
17	107	36	53	470
5	112	10	22	502
10	122	21	33	556

The step of 23 was too large to have its immediate effect balanced by the compensating coil in the position in which the coil was set. The magnetic effect of such a large step is conjecturally shown by the broken line marked (?) in fig. 4. It will be noticed that the points reached after 1 minute at each step lie well on a continuous curve, which is shown by a dotted line in the figure.

In Table II and fig. 4 one scale division of magnetising current is equivalent to 0·00362 c.g.s. units of magnetising force, and one scale division of the magnetometer is equivalent to 0·0177 c.g.s. units of $\mathfrak{I}$. The immediate value of $d\mathfrak{I}/d\mathfrak{H}$ is about 10, as before, and this applies approximately throughout the range of magnetism dealt with here, with a slight increase towards the upper end of the range.

Higher up in the curve of magnetisation, however, the immediate effect of a small quick increment of magnetic force is greater, though then (owing to the greater steepness of the curve $\mathfrak{I}$ and $\mathfrak{H}$) it bears

FIG. 4.



a smaller proportion to the ultimate effect. This is well shown in the following experiment (Table III and fig. 5).

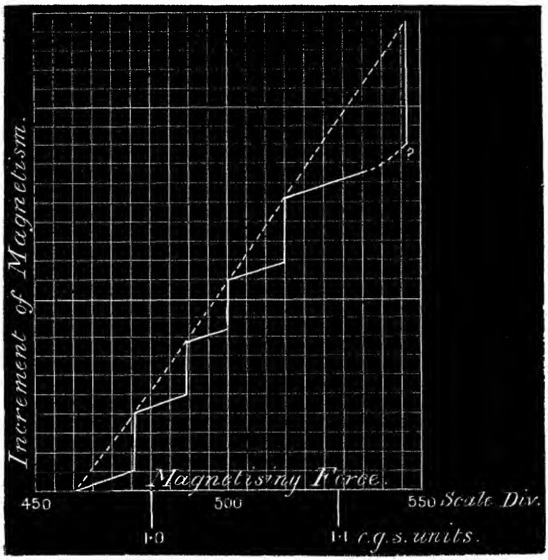
Table III.

Magnetising current.		Magnetising effect.	
Step.	Total.	Immediate.	Additional in 1 minute.
—	461	—	—
15	476	19	61
13	489	17	55
11	500	14	50
15	515	19	69
32	547	(41+)	(142−)

Here the last step was too large for perfect compensation. One scale division of current corresponds to 0·0021 c.g.s. units of magnetising force, and one scale division of the magnetometer corresponds to 0·022 of $\mathfrak{I}$. The immediate susceptibility to small increments of force, $d\mathfrak{I}/d\mathfrak{H}$, is now about 13. The magnetic viscosity is now so

great that this immediate effect is less than one-fourth of the whole change which the magnetisation has suffered by the time 1 minute has elapsed.

FIG. 5.

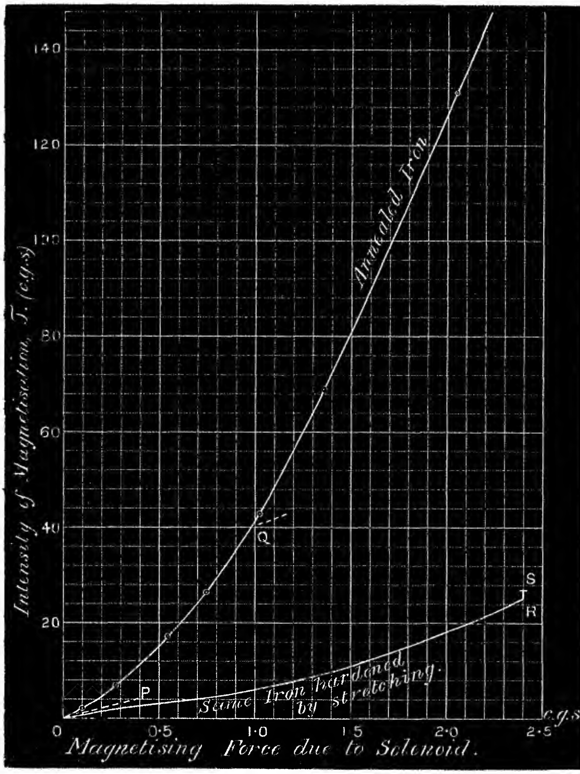


To show clearly the region in the curve of magnetisation at which the experiment of Table III and fig. 5 was made, a curve is drawn in fig. 6, showing, as the result of a separate experiment, the relation in absolute measure of the intensity of magnetism to the magnetising force produced by the solenoid. The region dealt with in Table III is at the place marked Q ($\mathfrak{I}$ = about 40 c.g.s.), and the dotted line drawn there shows the immediate value of $d\mathfrak{I}/d\mathfrak{H}$ after a 1-minute pause. The dotted line P shows the corresponding initial gradient, or immediate value of $d\mathfrak{I}/d\mathfrak{H}$, when there is no previous magnetisation.

Another step-by-step experiment of the same kind, made at a place higher up, where the magnetising force of the solenoid was about 4 c.g.s. and $\mathfrak{I}$ about 320, gave again about 13 for the immediate effect ($d\mathfrak{I}/d\mathfrak{H}$); and this was followed by a creeping to the extent of six or seven times the immediate effect.

The immediate magnetic effect of a small step is substantially the same whether the step is made quite suddenly by short-circuiting a resistance coil in the circuit of the magnetising solenoid, or comparatively gradually by means of the liquid slide, so that the process occupies a sensible fraction of a second, or even as much as a whole second.

FIG. 6.



However small the step is it appears to be followed by a creeping up of magnetism. I have been able to discover nothing which would correspond with the limit of perfect elasticity in straining a solid (if there be any true limit of elasticity), either in the initial part of the process of magnetisation, or after the prolonged application of a constant magnetising force.

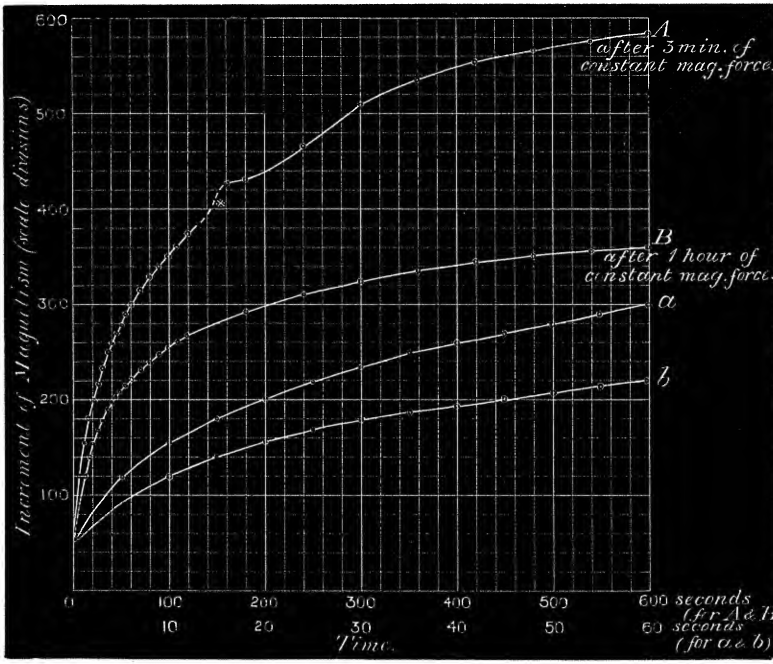
But the prolonged application of a constant magnetising force produces an effect which is a most interesting anologue of one effect of prolonged loading in a stretched wire. It is well known that when a load (sufficiently great to produce permanent set) is applied to a stretched iron wire, there ensues, with the lapse of time, not only a certain amount of supplementary viscous extension (the analogue of the magnetic creep) but also a quasi-hardening of the metal which becomes manifest when an addition is made to the load.* One effect

* *Cf.* 'Roy. Soc. Proc.,' No. 205, 1880, or 'Encycl. Brit.,' art. "Strength of Materials."

of this is that the wire responds with great sluggishness to the additional load, and this sluggishness is greater the longer has been the preceding interval during which the load has been maintained constant. To test whether, in like manner, the prolonged application of a constant magnetising force would produce what may be called magnetic hardening, I have made comparative observations of the time-rate of change of magnetism when a definite small increment of force is applied, the preceding force having been kept constant (*a*) for a short time and (*b*) for a long time. The result is to show that the process of magnetic creeping after a small step is much slower when the preceding force has been in action for a long time than when it has been in action for only a short time.

The following experiment illustrates this well. After raising the magnetising force to between 2 and 3 c.g.s. units, the compensating coil was adjusted to balance the immediate effect of a small increase of force, this increase being brought about by short-circuiting 1 ohm (out of many ohms) in the magnetising circuit. When the compensation had been adjusted, the iron was demagnetised by reversals, and the magnetising force was again gradually applied. When it reached the value of 2·54 c.g.s., a pause was made for 3 minutes, during which time this magnetising force of 2·54 remained constant. The resistance in the circuit of the magnetising current was then suddenly reduced by 1 ohm, which had the effect of raising the force to 2·60. The compensating coil prevented this step-up of magnetising force from having any instantaneous effect on the magnetometer; but creeping, of course, began at once, and the time-rate of creeping was observed during 10 minutes. Then the magnetising current was kept constant for 50 minutes more, making 1 hour in all, and a second step-up of magnetising force was effected by removing another ohm of resistance: the second step was very nearly equal to the first, and raised the force to 2·66 c.g.s. The time-rate of creeping which followed it was also observed during 10 minutes. The results are shown in fig. 7, where the curve A shows the growth of magnetism during 10 minutes when the step had been preceded by a 3-minute interval of constant force, and the curve B shows the growth of magnetism when a sensibly equal step was made, which had been preceded by a 1-hour interval of constant force. The times are in each case reckoned from the instant at which the step was made, and the increment of magnetism is in each case reckoned from the value reached just before the step was made. The immediate effect of each step (balanced by the coil) was equivalent to 51 scale divisions of the magnetometer. The creeping-up in 10 minutes was equal to no less than 531 scale divisions in the case of curve A, as against 320 in curve B. At the place marked with an asterisk in curve A, it happened that the laboratory door was slammed,

FIG. 7.



which shook the wire very perceptibly and caused a comparatively sudden increase of magnetism (indicated by the dotted part of the curve), after which the time-rate of creeping became specially slow for 1 or 2 minutes: finally, however, the rate appeared to recover from this disturbance. The curves *a* and *b* of fig. 7 are the first parts of A and B drawn to a ten-fold coarser scale of times.

In confirmation of the above, another experiment was made in which the magnetic force was increased by three successive small and very nearly equal steps. The first step was made after 5 minutes of constant force, the second after 1 hour of constant force, and the third again after 5 minutes of constant force. Time-curves of the growth of magnetism were drawn in all three cases. The first and third curves were not far from coincident; but the second curve lay very much below them, as B lies below A.

In the experiments to which figs. 4, 5, and 7 relate, the increment of magnetic force whose effects were measured was preceded by increasing magnetic forces: in other words, it was a step-up from a point on the *up* curve of magnetisation. I have also examined the effect of a small *step-down* from a point on the up curve—that is to say, a small decrement of previously increasing force—and find, as

might perhaps be anticipated from what we knew about static hysteresis, that the immediate effect ($d\mathfrak{I}/d\mathfrak{H}$) of a step-down is decidedly less than the immediate effect of a step-up. When the compensating coil had been adjusted to balance the first effect of a step-up, it was found to give over-compensation for a step-down.

Another process has been examined, namely, the alternation of a step-up with step-down, many times repeated. After the magnetising current had been raised to a certain value, it was periodically altered through a definite narrow range by alternately putting in and pulling out the short-circuit plug of a small resistance coil in the main circuit, or by making and breaking a feeble circuit in a second solenoid wound over the first. It was only when this process had been repeated many times that the magnetic effects of the small changes of $\mathfrak{H}$ became approximately cyclic; the early cycles were associated with a progressive rise in the intensity of magnetism. But when a nearly cyclic state was reached, the compensating coil could be adjusted to balance the immediate effects of $+\delta\mathfrak{H}$ or $-\delta\mathfrak{H}$, and the same adjustment of course served to balance either.

Tested in this way the gradient $d\mathfrak{I}/d\mathfrak{H}$ (for the immediate effect of $\delta\mathfrak{H}$ after many small + and − steps) has of course a lower value than the gradient which is found when $\mathfrak{H}$ is first raised to $\mathfrak{H}+\delta\mathfrak{H}$. The latter, as we have seen, is greater when the magnetisation is moderately strong than when there is little or none. The former is nearly constant throughout a wide range of $\mathfrak{I}$; its value is approximately the same as at the initial part of the magnetisation curve—namely 10—until the region of saturation is approached, when it becomes distinctly less.*

The periodic changes of magnetism which are brought about by successive small increments and decrements of $\mathfrak{H}$ exhibit a lagging and creeping up and down precisely similar to that which has been illustrated in fig. 1. That figure may serve to show in a general way the relation of the change of $\mathfrak{I}$ to the change of $\mathfrak{H}$, when at any place in the curve a very small increment $\delta\mathfrak{H}$ has been applied and removed often enough to establish a cyclic *régime*. I have not made any full examination of the variation which under these conditions the gradient $d\mathfrak{I}/d\mathfrak{H}$ suffers when the magnetism on which the small cycle if superposed is gradually pushed up towards saturation, nor of the proportion which the subsequent creeping up or down bears to that part of the change of $\mathfrak{I}$ which occurs immediately on the application or removal of $\delta\mathfrak{H}$. The creeping which follows each repeated application and removal of $\delta\mathfrak{H}$ is certainly much reduced when the iron approaches saturation; but the immediate effect is also reduced, and so far as may be judged by rather rough determinations, it appears

* *Cf.* Lord Rayleigh, *loc. cit.*, on the approximate constancy of the *static* gradient $d\mathfrak{I}/d\mathfrak{H}$.

that the proportion of creeping to immediate effect is much the same with high as with low magnetisation.

One may refer, in this connexion, to the energy which is dissipated through hysteresis, in performing a small cycle by alternately applying and removing a very small force $\delta\mathfrak{H}$. The action is the same in kind whether there is or is not additional magnetisation. The energy dissipated in each cycle is $-\int\mathfrak{I}d\mathfrak{H}$, and vanishes when the increment and decrement of $\mathfrak{I}$ go on *pari passu* with the increment and decrement of $\mathfrak{H}$.

Consider now fig. 1. When the repeated cyclic changes of $\mathfrak{H}$ are indefinitely rapid and go on without pause, so that creeping has not time to occur, a single straight (or sensibly straight) line such as OA represents the relation of the change of magnetism to the (very small) change of magnetising force, during both increment and decrement. The rapidity of the action prevents any loop from being formed, and there is consequently no sensible dissipation of energy through hysteresis. This state of things is perhaps nearly realised in the case of a vibrating telephone diaphragm, or, in regard to circumferential magnetisation, by an iron conducting wire in a telephone circuit. Again, let the cycle be performed indefinitely slowly. In that case the magnetism, at every stage of the cycle, creeps up or down to a steady value. A sensibly straight line, such as OB, represents the relation of $\mathfrak{I}$ to $\mathfrak{H}$ during both increment and decrement; and there is again no dissipation of energy. But with any frequency of alternation lying between these extremes of infinitely fast and infinitely slow, a loop will be formed, since the creeping will take effect most considerably at and near the ends of the range (the time-rate of change of $\mathfrak{H}$ being least there), and there will be dissipation of energy. When the limits and mode of variation of $\mathfrak{H}$ are specified, there must be some particular frequency which will make the energy dissipated per cycle a maximum.

The phenomena described in the paper have been reproduced in several specimens of annealed iron wire, of course with quantitative differences. As to the amount of magnetic creeping much depends on the annealing of the specimen. Another piece of iron wire cut from the same bundle as the piece with which these experiments were made, and annealed at another time, showed almost exactly the same susceptibility to magnetism as the first piece, so far as immediate effect went; but in it the subsequent creeping up was decidedly less (in the proportion of about 4 to 5).

When the iron is hardened by mechanical strain the phenomena of creeping vanish almost completely. A specimen from the same bundle was annealed, and showed much creeping. It was then put in the testing machine and pulled until it took a set of 1 or 2 mm.

in a length of 40 cm. or so. It was then examined magnetically as before, and scarcely a trace of creeping could be observed when a feeble magnetising force was applied. When the compensating coil was properly adjusted the making or breaking of the magnetising current caused no more than a slight momentary quiver of the magnetometer needle, followed by no measurable drifting, although the whole magnetic effect (compensated by the coil) was equivalent to a hundred or more scale divisions. When a magnetising force of as much as 0·6 c.g.s. unit was suddenly applied, the amount of creeping, if there was any, was certainly less than 1 per cent. of the immediate effect. With values of $\mathfrak{H}$ higher than this it became possible to detect creep with certainty. The following notes relate to this wire :—

Magnetising force suddenly applied. (c.g.s.)	Immediate value of $\mathfrak{I}$ (c.g.s.).	
0·75	4·49	
1·28	8·42, crept in 1 min. to	8·58.
2·40	25·5 ,,	26·4.

These forces were in each case applied to this wire in a neutral state. Another trial of the same, with feebler forces, gave 5·3 as the value of $d\mathfrak{I}/d\mathfrak{H}$ for the immediate effect of a very small force, applied when the iron was demagnetised. The same quantity in the annealed specimen was, as has been said, about 10. In fig. 6 the relation of $\mathfrak{I}$ (immediate) to $\mathfrak{H}$ as stated above, is represented by the curve OR; the creeping up at the last point is RS.

In speaking of soft iron it has been shown that the effects of creeping are most marked when a small addition $\delta\mathfrak{H}$ is made to a previously increasing force $\mathfrak{H}$. In instances quoted above, the creeping up in 1 min. has under those conditions been many times greater than the immediate effect of $\delta\mathfrak{H}$.

By way of putting the specimen of hardened iron to the same test, I have applied a magnetic force of 1·46 and raised it by a small step to 1·49. The immediate effect of this step (which was balanced by the compensating coil) was equivalent to twenty-two scale divisions of the magnetometer, and this was followed during 1 minute by a creeping equal to six scale divisions. In itself this creeping is considerable, but compared with the corresponding creeping in soft iron it is extremely small.

Pieces of steel (containing a good deal of carbon) have also been examined, with the result that whether the steel be annealed or in its commercial temper the phenomenon of creeping is even less visible than in hardened iron. With annealed steel, a force which produced an immediate (compensated) magnetic effect equal to 124 scale divisions caused barely a single scale division of creeping. With a stronger current, giving an immediate magnetism of 340, the sub-

sequent creeping was 3. In steel and in hard iron the creeping seemed to be completed in a few seconds after the institution of the magnetising current. The steel specimen, like the iron, had a diameter of rather more than 4 mm. Its susceptibility (annealed) was considerably less than that of the iron in the hard state.

It is scarcely necessary to observe that the protracted and extensive creeping or magnetic "nachwirkung" in soft iron which these experiments illustrate cannot be ascribed to the subsidence of the circumferential currents which are generated by the imposition of longitudinal magnetic force. The creeping is equally conspicuous whether the magnetic force is suddenly or gradually imposed. Lord Rayleigh has shown that circumferential currents started and left to themselves will subside to e^{-1} of their initial magnitude in the time

$$\tau = \frac{4\pi\mu a^2}{(2{\cdot}404)^2 \rho},$$

where a is the radius of the cylinder, μ its permeability, and ρ its specific resistance.* In the present instance, taking the case of the annealed iron rod, $a = 0{\cdot}202$, $\mu = 125$, $\rho = 9827$ (Everett), and τ is less than $\frac{1}{1000}$ of a second. The subsidence would be practically complete in a small fraction of a second: but the creeping persists during many seconds and even minutes with no excessive change of rate. Again, comparing soft iron with hard iron, in which μ is less and ρ is greater, the values of τ will differ, but not by any means so much as to correspond with the very wide difference in magnetic lag.

In view of this it is puzzling to find that the diameter of the rod experimented upon has a most important influence on the magnetic lag.

In testing various samples of soft iron wire, most of which were of less diameter than the piece used in the above experiments, I noticed that the phenomena of creeping were less marked in the smaller rods. I then tried a bundle of nine very soft annealed iron wires, which were bound together with fine copper wire, and formed a core of about the same length and aggregate diameter as that of the solid rod formerly used. With this bundle there was some creeping, but very little in comparison with what was observed in the solid rod, as the following notes show:—

Bundle of nine soft Iron Wires.

Magnetic force $\mathfrak{H}$ suddenly applied (c.g.s.).	Magnetometer deflections. Immediate (balanced by compensating coil).	Subsequent creeping in 1 min.	Total in 1 min.
0·052	17	2	19
0·147	52	9	61

* 'Brit. Assoc. Report,' 1882, p. 446.

Finally, another bundle was built up, consisting of a much larger number of fine annealed iron wires. With this the creeping was almost insensible.

It may be that the comparative absence of magnetic creeping, or "nachwirkung," in these last experiments is to be ascribed to the quickness with which the process of creeping completes itself in a finely divided mass of iron: in other words, that the process is practically complete in a time much shorter than the period of the magnetometer needle. The marked difference in effect between a solid core (a single thick wire) of soft iron and a laminated core (a bundle of fine wires) of the same material, suggests that in the former much more than in the latter the process of creeping is retarded by the eddy currents which are set up by those molecular movements in which the process itself consists.

[July 11th.—In seeking an explanation of the difference in behaviour it may be worth while to bear in mind that there is probably a considerable difference in molecular structure between a solid core and a laminated core of iron. If we accept the view that the magnetically neutral state is due to the molecular magnets forming closed rings, these rings will for the most part be closed within the limits of the separate constituent pieces of the laminated core, whereas in the solid core they may be much larger, their dimensions being limited only by those of the core itself.]

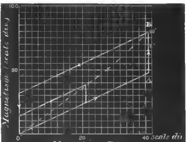
I have received very valuable help in these experiments from two students, Mr. David Low and Mr. William Frew, who have prosecuted a troublesome research with much patience and zeal.

III. "Note on the Thermo-electric Position of Platinoid." By J. T. Bottomley, M.A., F.R.S., and A. Tanakadate, *Rigakusi*. Received June 13, 1889.

In carrying out a series of experiments on radiation of heat by solid bodies, an investigation to which one of the present writers has for some time past devoted considerable attention, it became necessary, for a purpose which need not here be detailed, to select a thermo-electric pair of metals, of which one metal is essentially platinum, as it passes through glass. Various pairs were considered, and some trials were made; and it was finally determined to make use of platinum and platinoid. The latter metal is an alloy whose electrical and mechanical properties were investigated some years ago by one of the present writers;* and since that time it has

* J. T. Bottomley, 'Roy. Soc. Proc.,' 1885.

FIG. 1.



100
50
0
20
40
scale div
Magnetism (scale div)
Magnetising Force.
B

Fig. 2.

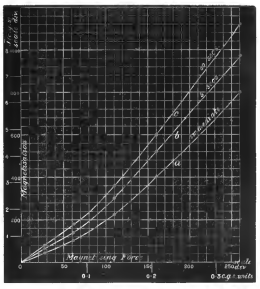
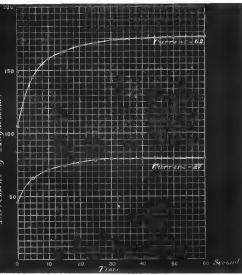

scale div.
8
1000
7
800
6
5
600
4
400
3
2
200
1
Magnetisation
60 secs
5 secs
immediate
c
b
a
Magnetising Force
0
50
100
150
200
250
scale div
0·1
0·2
0·3 c.g.s. units

Fig. 3.



200
150
100
50
0
10
20
30
40
50
60
Current = 62
Current = 27
Increment of Magnetism.
Time
Second

Fig. 4.

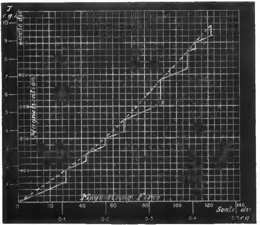

I
c.g.
Scale div
Magnetization
Magnetising Force
0
20
40
60
80
100
120
140
Scale div
0·1
0·2
0·3
0·4
0·5 c.g.
1
2
3
4
5
6
7
8
9
10

FIG. 5.

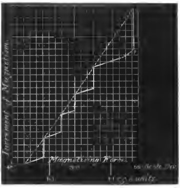


Fig. 6.

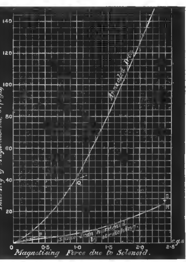
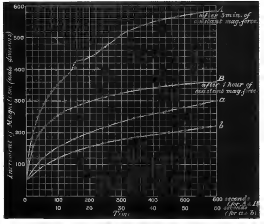

140
120
100
80
60
40
20
0
0·5
1·0
1·5
2·0
2·5
c.g.s
Intensity of Magnetisation, I, (c.g.s)
Magnetising Force due to Solenoid.
Annealed Pipe
Q
P
B
A

FIG. 7.


600
500
400
300
200
100
A
after 3 min. of constant mag. force.
B
after 1 hour of constant mag. force.
a
b
Increment of Magnetism (scale divisions)
0
100
200
300
400
500
600 seconds (for A & B)
10
20
30
40
50
60 seconds (for a & b)
Time